SPACE SHUTTLE PLUME CONTAMINATION

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The Space Shuttle Orbiter uses earth storable bipropellant propulsion systems for attitude control and orbit change maneuvers. This propulsion system has a demonstrated high performance and realiability, but the rocket engine combustion products are much more complex than the products of hydrazine monopropellent decomposition or cold gas propulsion. These products of combustion can deposit or condense on surfaces in the vicinity of the rocket engine, and can cause a degredation in system efficiency.

Studies were conducted to identify the plume contamination potential for the primary and vernier thrusters of the Space Shuttle Orbiter. These studies indicate that plume transported contamination does not impinge or condense on the surfaces of the Orbiter, but some potential does exist for the flow of fuel film contaminant down the wall of the exhaust nozzle and off of the nozzle lip when short pulse widths and cold combuster walls are encountered. Contamination of Space Shuttle deployed payloads will be negligible since only the vernier thrusters are operated during this portion of the mission. The high performance of these engines will result in negligible plume contamination regardless of their orientation.

1. INTRODUCTION

The Space Shuttle Orbiter has two reaction control subsystems that perform a number of operations within the Space Shuttle mission profile. Figure 1 shows the location of the forward reaction control engines mounted in the surfaces on the sides of the nose section of the Orbiter, and on the top surface ahead of the pilot's compartment, and the aft reaction controls mounted on the extensions of the orbital maneuvering system pods. The forward RCS engines are primarily used in conjunction with the aft RCS engines for exoatmospheric flight maneuvering commencing with external tank separation. They can also be used in the atmosphere for external tank separation during return to launch site, and mission abort maneuvers in conjunction with the aft RCS engines. The aft RCS system, in addition to the RTLS function mentioned, also provides the primary control for transulation from orbit to conventional flight. There

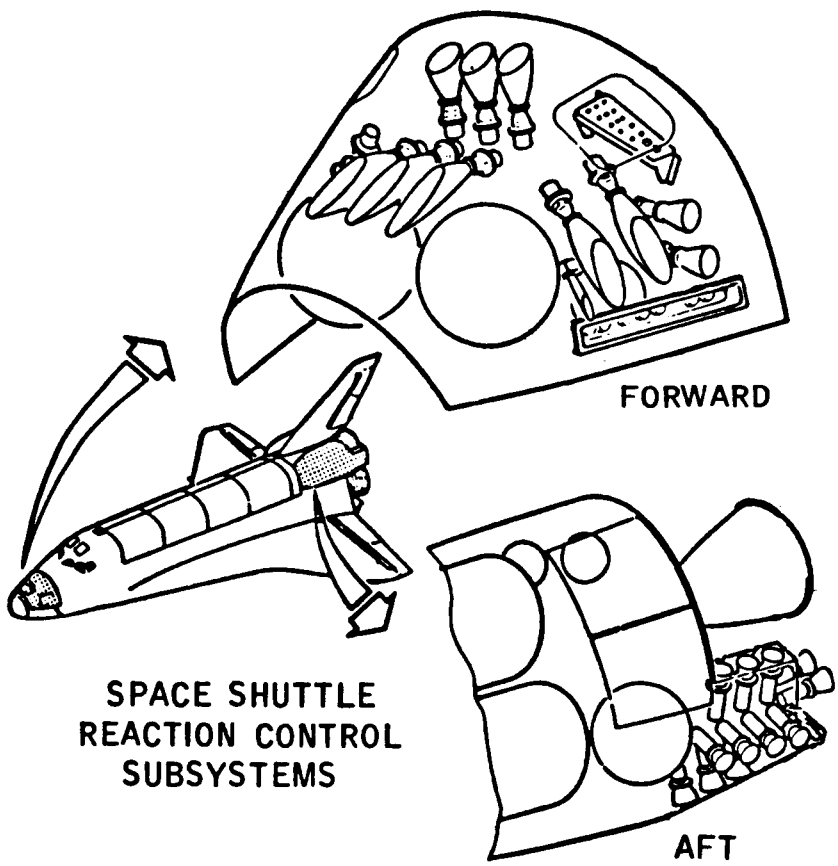

FIGURE 1

SPACE SHUTTLE REACTION CONTROL SUBSYSTEMS

are thirty-eight primary thrusters which generate 870 pounds of thrust at nominal inlet conditions. These thrusters are not presently operated during payload deployment. There are also six RCS vernier thrusters of 25 pounds thrust which are operated during the payload deployment. Figures 2 and 3 show photographs of two versions of these thrusters. Studies have been conducted to determine the influence of the rocket exhaust plumes on the spacecraft shuttle surfaces and on the deployed payloads. Initial results indicate that little or no orbiter contamination will result from the firing of these engines due to the high efficiency and minimum injector manifold volume of the engines. The payloads are deployed when the primary engines are not operating. Future shuttle missions, however, may incorporate spacecraft deployment manuevers and auxiliary power svstems which may be exposed to the exhaust plumes of both the primary and vernier thrusters. Therefore, a discussion of the nature of the rocket engine plume and the contamination that can result from it are important if one is to prevent contamination of sensitive surfaces on these future systems.

2. THRUSTER DESIGN CHARACTERISTICS

The nature of rocket engine plume and the concentration, velocity, and location of potential contaminants, whether they are solids, liquids or gases, are strongly influenced by the characteristics of the rocket engine. The areas of the engine design which influence the rocket plume are the volumes between the valve seats and the injector face (dribble volume), the propellent flow distribution over the face of the injector, the temperature of the propellent and engine hardware, and the shape of the combustion chamber and exhaust nozzle.

Pulsing operation and steady state operation are known to produce different plume characteristics. During the steady state firings, combustion is relatively efficient and the major plume constituents are those predicted from equilibrium thermodynamic considerations. Even at steady state conditions, most rocket engines have a variable mixture ratio distribution because of the injector pattern, film cooling and dynamic consideration. The composition of the rocket exhaust plume therefore varies as a function of radial distance from the plume center line. Some rocket engine injection patterns are asymmetrical and the plume composition thus varies with angular position around the engine center line. With film cooled engines, such as the Space Shuttle primary thruster, the outer regions of the plume are relatively rich in the propellent used as the film coolant (monomethylhydrazine) and its decomposition products.

FIGURE 2 SPACE SHUTTLE REACTION CONTROL SUBSYSTEM PRIMARY THRUSTER

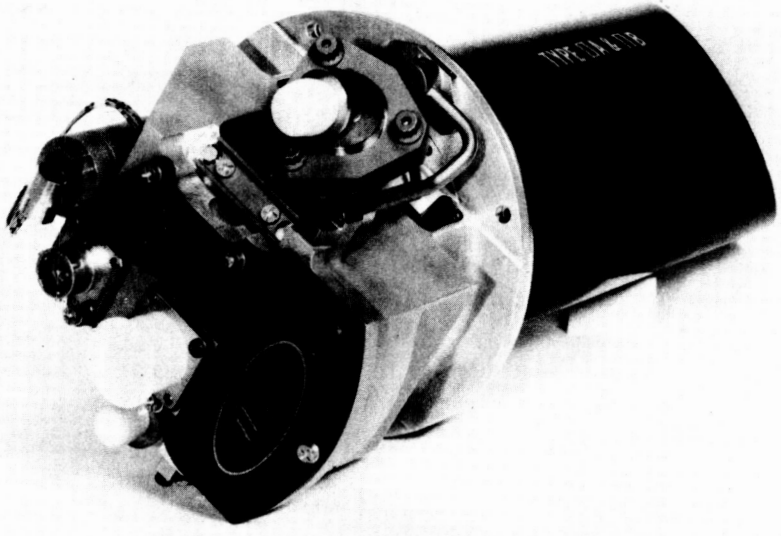

FIGURE 3 SPACE SHUTTLE REACTION CONTROL SUBSYSTEM VERNIER THRUSTER

Figure 4 shows a typical exhaust plume profile with superimposed mixture ratio distribution.

Pulse firing of rocket engines introduces special factors which are probably of the most importance in the consideration of plume contamination. Performance at short pulse widths is lower than steady state values because the start-up and tail-off transients are a releatively large fraction of the total pulse time. During these transients, unreacted fuel and oxidizer and intermediate products of combustion are formed. At low engine and surface temperatures, condensable materials may accumulate on the internal surfaces of the engine and the external surfaces of the spacecraft. Those materials accumulated on the internal surfaces may be transported to the external surfaces by both aerodynamic and hydrodynamic means.

The normal ignition process for a typical bipropellent is shown on Figure 5. When the propellent valves are opened, the fuel and oxidizer passages within the injector begin to fill with a mixture of propellent liquid and vapor. Propellent also begins to flow from the injector with a rate that increases as the injector fills with liquid. Eventually, the injector completely fills with liquid and the flow from the injector reaches its maximum value. During the starting transients, the propellent in the combustion chamber enter into preignition reactions which raise the temperature and pressure within the combustion chamber until ignition occurs. Some of the preignition reaction products differ from the products formed during steady state ignition.

The engine shut-down transient also influences plume characteristics. When the engine valves close, the pressure driving fuel and oxidizer into the chamber decreases towards the vapor pressure of the propellent and the propellent flow rates into the chamber diminish. A series of combustion pressure peaks occur during the shut-down transient period. Each peak temporarily slows the propellent flow into the combustion chamber. This cyclic combustion continues until the oxidizer passages in the injector are empty. The oxidizer is exhausted first because of its higher vapor pressure. Some fuel remains in the injector after combustion ceases, and this fuel continues to empty from the injector for many milliseconds after the oxidizer flow stops. Some of the shut-down fuel leaves the engine directly through the nozzle while some deposits on the combustion chamber walls and later leaves the engine under the influence of evaporation, gravity, surface tension, and shear from the combustion gases.

The processes taking place in the engine during pulsing operation cause the

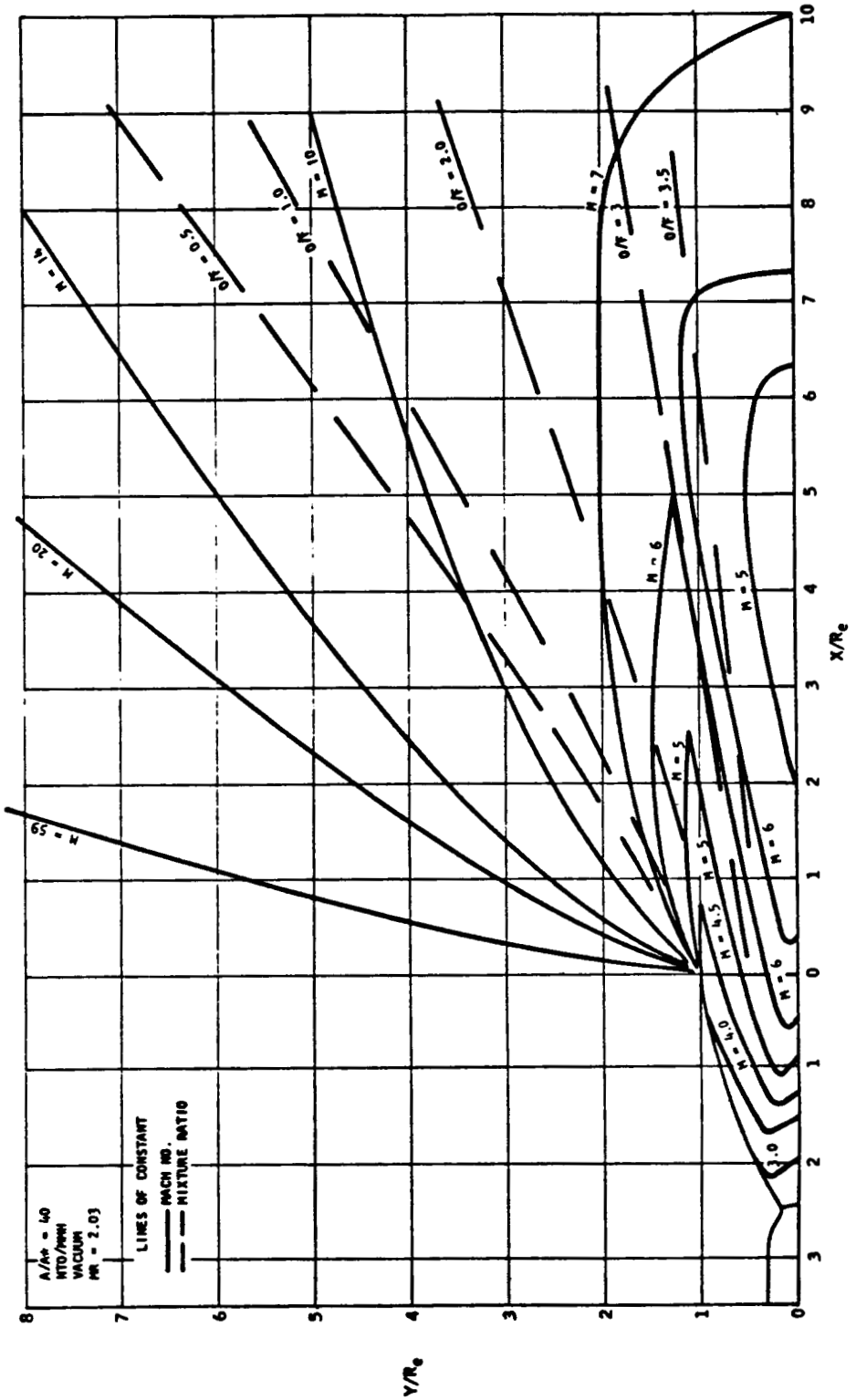

FIGURE 4

ROCKET ENGINE EXHAUST FLOW FIELD

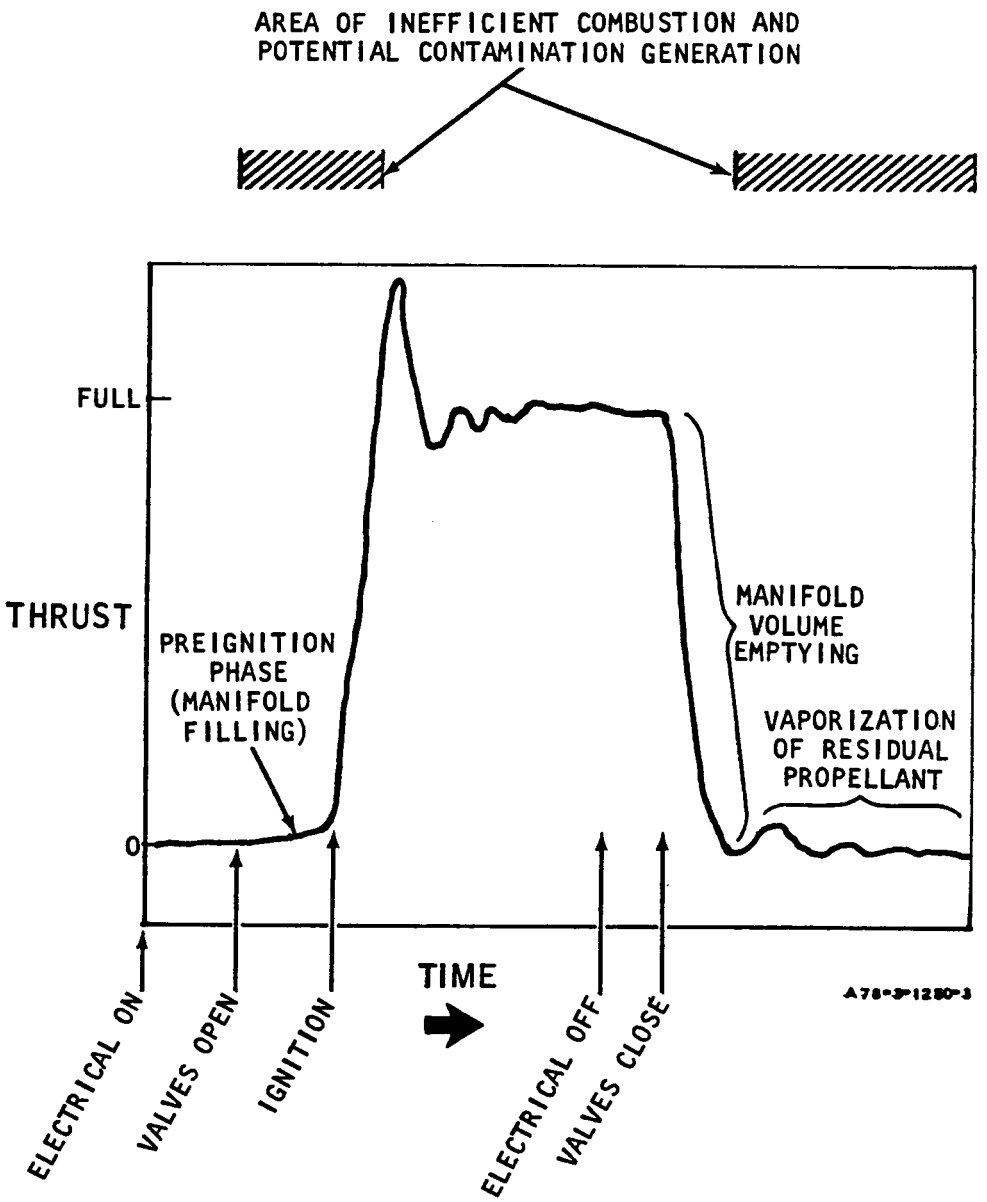

FIGURE 5

TYPICAL THRUST TRACE FOR REACTION CONTROL THRUSTER

plume to change rapidly with time. During portions of the pulsing duty cycle, the plume can consist almost entirely of oxidizer vapor, while at other times it may be rich in combustion products orfuel vapor. The designs of the 870 pound thrust primary thruster and 25 pound thrust vernier thruster are oriented towards minimization of plume contamination during both the pulsing and steady state operation. Minimization of the plume contamination during steady state operation is accomplished through a high performance injector. This injector assures that a maximum amount of the propellents are combusted, leaving little or no unreacted propellents to exit out through the exhaust nozzle. During pulsing operation the minimization of plume contamination is accomplished through a design of a minimum dribble volume injector. These two design criteria, (1) high combustion efficiency, and (2) minimum dribble volume, provide the basis for the minimization of plume contamination under all operating conditions. Experimental data and analytical calculations have verified that these criteria establish a basis for an engine design with minimum plume contamination.

3. EXPERIMENTAL DATA

Plume contamination tests have been conducted on various bipropellent rocket engines, ranging in thrust of less than 1 pound up to greater than 300 pounds thrust. (Ref 1-5) A majority of the tests were conducted on Marquardt's 25 pound thrust Vernier engine and the 100 pound thrust R-4D engine used on the

1. Etheridge and Boudreau, "Attitude Control Rocket Exhaust Plume Effects" Journal Spacecraft and Rockets, Vol 7, No 1, Jan 1970.
2. Stechman, R.C., and Thonet, T.A., "The Effect of Rocket Exhaust Impingement on Spacecraft Surfaces during Pulsing Engine Duty Cycles", JANNAF 12th Liquid Propulsion Meeting CPIA No. 201, Oct., 1970.
3. Arnett, Gary M., "Lunar Excursion Module R.C.S. Engine Vacuum Chamber Contamination Study", NASA TM 53859, July 8, 1969.
4. Yanizeski, G.M., "Thermal Control Coating Degradation by the Service Module Reaction Central System Rocket Exhaust During Skylab Missions" TM-1022-12, Bellcomm Inc., August 1970; Sept 1970.
5. Jack, John R., Spisz, E.W. and Cassidy, J.F., "The Effect of Rocket Plume Contamination on the Optical Properties of Transmitting and Reflecting Materials", AIAA Paper 72-56, 10th Aerospace Sciences Meeting, Jan 1972.

Apollo Service Module and Lunar Module. These two engines represent a large variation in engine dribble volume and the results of the tests indicate a definite correlation between engine dribble volume and plume contamination potential. Figure 6 shows a plot of contamination versus engine dribble volume. Also plotted on this Figure are data for Marquardt's 5 pound bi-propellant engine, and a 1 pound engine. This correlation while qualitive in nature, indicates that once the electrical pulse width to dribble volume ratio is greater than 5, the contamination potential becomes nil.

The R-40 primary thruster engine has a dribble volume equivalent of approximately 10 milliseconds. Operating at a minimum electrical pulse width of 40 milliseconds results in a ratio of 4, which would indicate that the engine would generate a very small amount of contaminant during its pulsing operation. The vernier thruster, with a dribble volume equivalent of approximately 8 3 milliseconds, operating at a 40 millisecond pulse width, would have a ratio of nearly 5, which again would indicate that the plume contamination caused by this engine would be nil.

Studies conducted by McDonnell Douglas in support of the Space Shuttle Orbiter Program (Ref 6, 7), using the CONTAM Program indicate that the potential for contamination is very small and verify the analysis previously discussed. The CONTAM Program provides an excellent basic analysis for determining the plume contamination potential. This analysis, however, uses a simplified combustion (TCC) model. The primary and vernier thrusters utilize film cooling and mixture ratio stratification which can not be effectively analyzed using the methodology of the program. Modifications of the CONTAM Program to include these effects are now being accomplished under Air Force Rocket Propulsion Laboratory funding.

Results of studies conducted by McDonnell Douglas and Marquardt indicate that there is some potential for contamination due to migration of liquids along the exit nozzle and around the lips of the nozzle during cold thruster

6. Oeding, R.C., et al, "Space Shuttle RCS Plume Contamination Study", MDC G5250, McDonnell Douglas Astronautics Company--west, July 1974.

7. Anon, "DOD Space Transportation System Payload Interface Support Study, Interim Report, Appendix C--Contamination Study", MDC G6367, McDonnell Douglas Astronautics Company--west, March 1976.

PLUME CONTAMINATION RESULTING FROM BIPROPELLANT NTO/MMH ROCKET ENGINE OPERATION

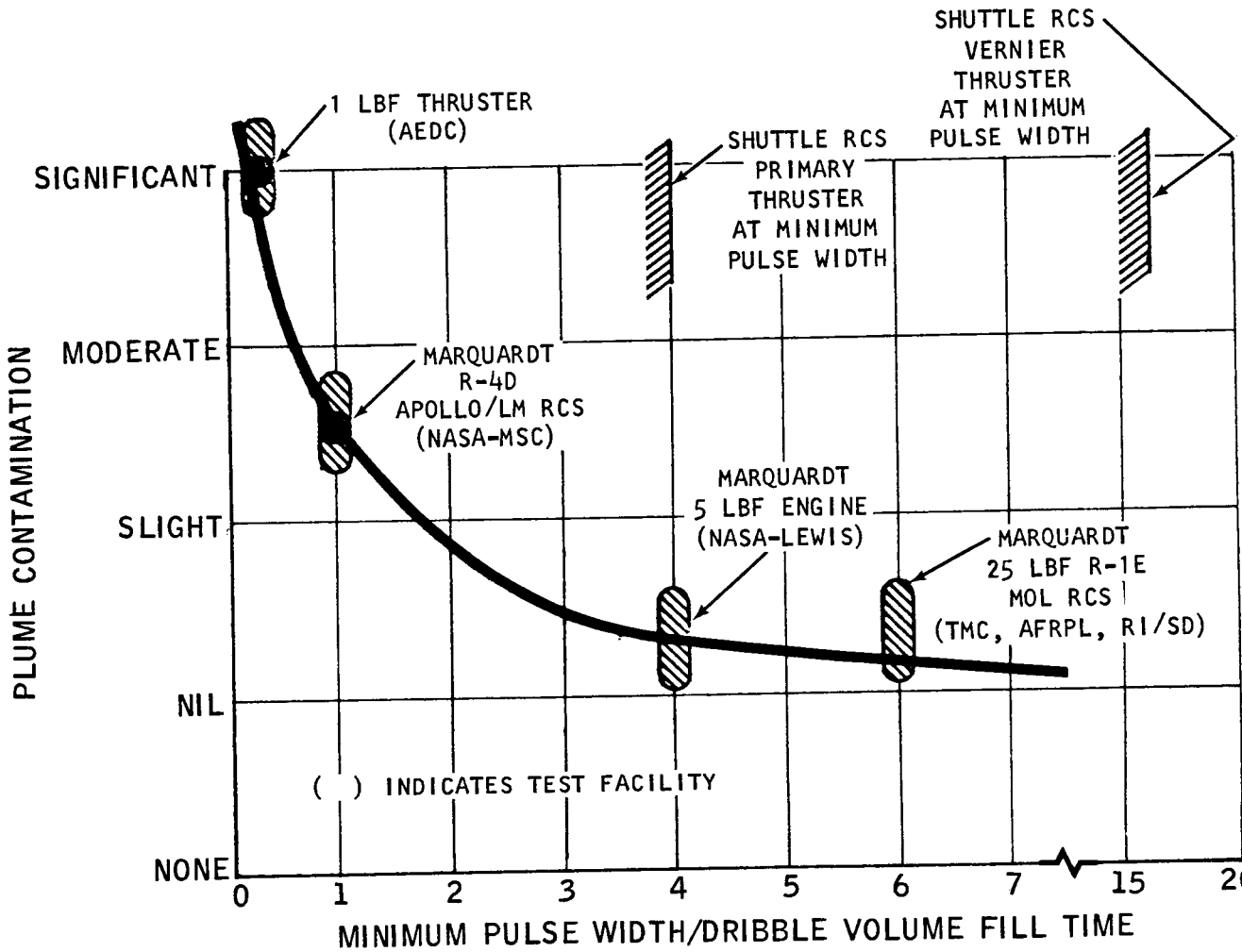

FIGURE 6

PLUME CONTAMINATION RESULTING FROM BIPROPELLANT NTO/MMH ROCKET ENGINE OPERATION